Performance Testing of Alternative Blowing Agents for Foam Insulation of Residential Water Heaters

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ABSTRACT

The U.S. Department of Energy (DOE) has requested the assistance of the Pacific Northwest National Laboratory to conduct analyses to determine if the energy efficiency requirements for electric, gas- and oil-fired residential water heaters should be revised. (Pacific Northwest National Laboratory is operated for DOE by Battelle Memorial Institute.) The performance of residential water heaters is measured by the Energy Factor (EF), a metric which accounts for both the efficiency of energy transfer to the water and the heat losses from the stored hot water to the environment. Residential water heaters are typically manufactured with 1 to 2 inches of foam insulation blown into the jacket with hydrochlorofluorocarbons (HCFCs) such as HCFC-141b. The insulation reduces the heat losses from the storage tank of the water heater, thus playing a role in meeting the DOE energy factor requirements. In accordance with the Montreal Protocol on ozone-depleting substances, the U.S. Environmental Protection Agency (EPA) has scheduled the phase-out of HCFC-141b for January 1, 2003. Several alternatives are being evaluated for blowing foam insulation. Examples of alternative materials being considered include hydrofluorocarbons (HFCs) such as HFC-245fa, HFC-356mffm, HFC-134a; cyclopentane; or water-based foams. Because there is little data on the performance of these foams in residential water heater applications, DOE initiated a study to evaluate their comparative performance. This paper reports on the details of the testing and evaluation of water heater performance using the alternative foam blowing agents. The results of this study are being used by DOE to evaluate the engineering and cost effectiveness of using alternative foam blowing agents for insulating water heaters in its revision of the residential water heater energy efficiency standards.

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BACKGROUND

The field of blowing agents that are commonly used for rigid polyurethane foams has undergone drastic changes since the Montreal Protocol was signed in 1987. In accordance with it, the EPA has scheduled the phase-out of HCFC-141b, the most popular alternative to CFC-11 (which had been banned even earlier in January 1, 1996), for January 1, 2003. Other countries of the world are working with other later dates for the phase-out of HCFCs. Alternatives to HCFCs are being investigated by several appliance/equipment industries to prepare the future for foaming insulation with materials that have zero Ozone Depletion Potential (ODP) and at the same time, an optimum performance for the particular application.

The search for blowing agents with zero ozone depletion potential has led to a number of candidates including hydrofluorocarbon (HFC) 245fa as a blowing agent and the addition of water to the foam formulation. The addition of water reacts with the isocyanate forming CO_2. In this paper the use of water to produce CO_2 as the blowing agent will be denoted as H_2O/CO_2. In the United States it appears that HFC-245fa has emerged as a leading candidate to replace HCFC-141b in the appliance industry

(Albouy et al. 1997, Logsdon et al. 1997). However, delays in the decision to build a manufacturing plant to produce HFC-245fa may force the water heater industry to use H_2O/CO_2 as the blowing agent.

In addition to environmental considerations, the selection of a blowing agent to replace HCFC-141b must also consider the thermal performance of the polyurethane foam. Residential water heaters sold within the United States must meet the current and future energy efficiency standards as specified by the U.S. Department of Energy (10 CFR 430, Subpart C).

DOE RULEMAKING PROCESS

Congress authorized the U. S. Department of Energy (DOE) to establish minimum energy conservation standards on products in 1975 with the passage of the Energy Policy and Conservation Act. In 1988, Congress passed the National Appliance Energy Conservation Act (NAECA) and established minimum energy standards. Many of these standards became effective in 1990 including those for water heaters. NAECA also established a timetable for future revisions of standards by DOE and for water heaters mandated two revisions of the standards.

In 1994, DOE proposed water heater standards that included performance levels for electric water heaters that could only be met by heat pump water heater technology. The Department was deluged with negative comments pointing out the high first costs, spaces were too small for heat pump water heaters, and that their reliability was poor. In 1995, Congress imposed a moratorium on new standards or analyses for all appliances during FY 1996.

Since 1996, DOE has developed a new process that includes more frequent and open dialogue with the stakeholders of any rulemaking. DOE has accomplished this for the water heater rulemaking by holding several public workshops and by private meetings with manufacturers and other key stakeholders. DOE has also developed more robust engineering and economic analyses. As part of the new analysis process, DOE contracted with the National Institute of Standards and Technology (NIST) to measure water heater performance with three polyurethane foam blowing agents, HCFC-141b, H_2O/CO_2, and HFC-245fa.

LITERATURE REVIEW

In a recent article on the topic of alternate blowing agents for refrigerated appliances, Sutej (1997) describes the three main candidates being considered to replace HCFC-141b. These are HFC-134a, HFC-245fa, and cyclopentane. Of the three, HFC-245fa most closely resembles HCFC-141b in all the physical properties. This liquefied gas (59°F boiling point) is non-flammable and can be used with current foaming equipment which is highly desirable for assembly-line foaming of water heaters, which is the currently used and the most cost-effective method. While not commercially available yet, HFC-245fa has posted early thermal conductivity results that are comparable to HCFC-141b. Although the blowing agent currently is in pilot plant production, the initial foam results are extremely promising and should be a serious contender to replace HCFC-141b throughout the refrigerator/freezer and water heater markets. However, HFC-245fa is expected to be more expensive than HCFC-141b, although to what extent (when it is produced in large quantities) is not clear.

A comparison of the physical properties of HCFC-141b, HFC-245fa and H_2O/CO_2 from Sutej (1997), McGee et al. (1996), Suzuki et al. (1996) and Barthelemy and Leroy (1995) is shown in Table 1.

Table 1. Physical Characteristics of HCFC-141b, HFC-245fa and H_2O/CO_2 blowing agents

Physical Characteristics	HCFC-141b	HFC-245fa	H_2O/CO_2
Chemical Formula	CH_3CCl_2F	$CHF_3CH_2CF_3$	H_2O ($\rightarrow CO_2$)
Molecular Weight	116.9	134.0	18
Boiling Point, °F (°C)	89.7 (32.1)	59.5 (15.3)	212 (100)
Flame Limits Volume, % (ASTM E-681)	7.6 - 17.7	none	none
Ozone Depletion Potential (ODP)	0.11	0	0
Halocarbon Global Warming Potential	0.12	0.21	--
Vapor Thermal Conductivity, Btu.in/hr.ft^2.F @111°F (W/mK @44°C)	0.084 (0.013)	0.097 (0.014)	0.125 (0.018)
Flammability	9.0 – 15.4% in air	Non	Non
Toxicity	Good	No adverse finding so far	Good
Solubility	Good	Good	Bad

Water heater foam systems using HFC-245fa were evaluated for stability, processability, physical properties, and energy performance and compared to those using HCFC-141b by McGee et al (1996). Their results of testing two water heater models foamed with each of these systems successfully using standard processing equipment showed that the energy factors of the two models as tested by the 24-hour DOE simulated use test were virtually identical.

Several of the water heater manufacturers have recently indicated that they would be reluctant to switch to HFC-245fa in their assembly lines since they cannot get a guarantee from Allied Signal company that it would be available in sufficient quantities (and low enough cost) for them to use by the 2003 timeframe. The alternative material they are looking at is the H_2O/CO_2 foam which also has a zero ozone depletion potential (ODP) and is cheap. However, its thermal conductivity is 46% higher than that of HCFC-141b and 30% higher than that of HFC-245fa (Suzuki at al. 1996) and its use for insulating appliances will result in a high energy penalty.

NIST TESTING DETAILS

The NIST testing was designed to quantify the performance of water heaters insulated with polyurethane foams using three different blowing agents – HCFC-141b, H_2O/CO_2, and HFC-245fa. The thermal conductivity of the foam was measured, as a function of mean temperature, using a guarded hot plate apparatus. Three sets of four electric residential water heaters, each insulated with the three polyurethane foams, were tested to determine the influence of the blowing agent on the water heater's energy factor and overall heat-loss coefficient (UA). A relationship between the overall heat-loss coefficient and energy factor was developed and compared to experimental results. An infrared imaging system revealed that areas surrounding the heating element access covers, the lower circumference of the water heater, and piping penetrations were significantly higher in temperature than the exterior surface of the water heater. The results of this study should be extremely helpful to water heater manufacturers in their selection of an appropriate blowing agent.

TEST SPECIMEN DESCRIPTION

Commercially available electric residential water heaters were selected for this study. The water heaters have a nominal capacity of 189 L (50 gallon) and contain two electrically-interlocked 4500-watt heating elements. These production units contain approximately 51 mm (2.0 in.) of polyurethane foam between the side and top of the storage tank and the exterior metal jacket. Glass-fiber insulation, approximately 25 mm (1 in.) thick, is positioned between the storage tank's bottom and exterior metal jacket. Twelve of these units, without the polyurethane foam, were manufactured and forwarded to a polyurethane foam supplier.

The polyurethane foam supplier subsequently insulated four water heaters and produced three sets of foam block specimens each set blown with one agent, HCFC-141b, H_2O/CO_2, and HFC-245fa. The foam block specimens' size, 660 mm x 660 mm x 66 mm (26 in. x 26 in. x 2.6 in.), was chosen to be compatible with the guarded hot plate apparatus. Each polyurethane foam's formulation and production date are documented in Table 2. Production dates were selected such that the elapsed time between the date of manufacture and testing were approximately equal, 28 days, for each foam formulation.

Table 2. Polyurethane Foam Formulations

Blowing Agent	**HCFC-141b**	**H_2O/CO_2**	**HFC-245fa**
Isocyanate Blend "A" Parts	1	1	1
Polyol Blend "B" Parts	1	0.65	0.81
Blowing Agent Percentage (%)	22.8	5.9	24.3
Polyol Temperature, °C (°F)	26.7 (80)	23.9 (75)	22.8 (73)
Isocyanate Temperature, °C (°F)	26.7 (80)	23.9 (75)	22.8 (73)
Cream Time, s	5	7	-
Gel Time, s	46	53	49
Tack Free Time, s	102	150	69
Free Rise Density, kg/m^3 (lb/ft^3)	23.68 (1.48)	24.0 (1.50)	23.4 (1.46)
Molded Density, kg/m^3 (lb/ft^3)	32.00 (2.00)	32.5 (2.03)	32.3 (2.02)
Production Date	4/21/98	6/2/98	7/8/98

EXPERIMENTAL APPARATUS

1-Meter Guarded Hot Plate

The thermal conductivity of the foam specimens was measured using a 1-meter guarded hot-plate (Figure 1). The apparatus has been used to develop Standard Reference Materials that permit industry, academic, and government laboratories to calibrate their "in-house" instrumentation and provide traceability to national and international standards. The main components of the apparatus are a guarded hot-plate and two isothermal cold surface plates as shown in Figure 2. The guarded hot-plate includes a metering section used to measure the heat flow into the test specimens and a guard section to minimize heat flow from the metering section in the radial direction. Guarding at the edges of the specimens is provided by an environmental chamber maintained at the mean temperature of the hot and cold plates. For this study, the apparatus was operated in the double-sided mode of operation, that is, two specimens produced with each of the three blowing agents are positioned between the hot plate and cold plates. The thermal conductivity measurement represents the average of the two specimens.

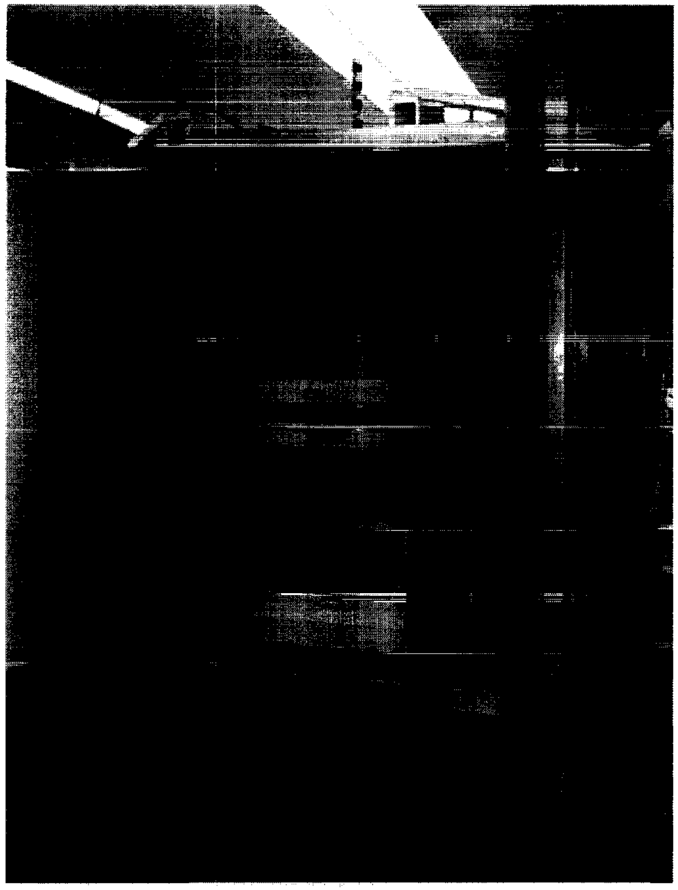

Figure 1 1-Meter Guarded Hot Plate Facility

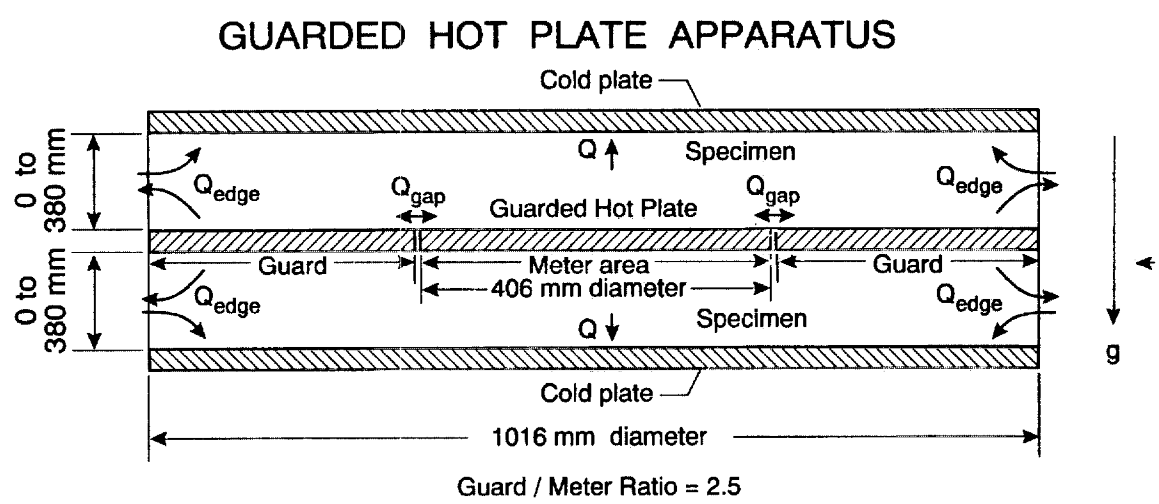

Figure 2. Schematic of 1-meter Guarded Hot Plate

Residential Water Heater Test Facility

A laboratory, dedicated to the evaluation of residential water heaters, was used to measure each water heater's energy factor and overall heat-loss-area coefficient. The water heater under evaluation was placed on a platform with piping connections in accordance with the Department of Energy's (DOE) "Uniform Test Method for Measuring the Energy Consumption of Water Heaters" (10 CFR 430, Subpart B). Thermocouples measured the water temperature entering and leaving the water heater, the temperature of the water within the water heater at six specified locations, and the surrounding ambient temperature. A weigh tank, positioned on a load cell, captured the water withdrawn from the storage tank during each of the six hot water draws. A digital power analyzer measured the energy consumed by the water heater.

The output signals of the thermocouples, load cell, and digital power analyzer were recorded using a computer-controlled data acquisition system. Every 30 seconds, the output signal of each transducer was measured, converted to engineering units, and calibration corrections applied. The results were displayed on the computer's monitor and archived to a floppy diskette. During the removal of heated water, the output signals of inlet and outlet thermocouples and the load cell were measured, converted to engineering units, corrected, and recorded every three seconds.

The computer-controlled data acquisition system also controlled the opening and closing of two solenoid valves. Two minutes prior to removal of hot water, a solenoid valve positioned at the discharge of the weigh tank was closed. Thirty seconds prior to the removal of heated water, the load cell was used to measure the tare weight of the weigh tank. At the prescribed times, the discharge pipe's solenoid valve was opened and the draw commenced. The draw continued until the output signal of the load cell indicated that the desired quantity of hot water had been removed. The solenoid valve on the discharge pipe was closed, a final measurement of the load cell made, and the weigh-tank solenoid valve opened to release the captured water.

The apparatus used to measure the overall heat-loss coefficient was similar to that used to measure the energy factor. Unlike the energy factor apparatus, however, the weigh tank, load cell, and associated solenoid valves were not present. Every 10 minutes, the computer interrogated the digital power analyzer and data acquisition system to update the quantity of energy consumed by the water heater and measured the output signals of the six thermocouples within the storage tank and the ambient thermocouple. The output signals were subsequently converted to engineering units, corrected in accordance with calibration data, displayed on the computer's monitor and archived to a floppy diskette.

A water-conditioning loop provided supply water at the prescribed temperature during tests to measure the water heater's energy factor. The water-conditioning loop consisted of three 303 L (80 gallon) storage tanks connected in series, an external chilled water-to-water heat exchanger, immersion heaters within the storage tanks, pumps, and an electronic temperature controller. The pumps were used, in conjunction with a fluid loop, to continuously circulate conditioned water past a pipe that supplied water to the water heater. The water conditioning loop allowed the inlet water temperature to vary from approximately 5°C (41°F) to 60°C (140°F). During this study, the inlet fluid conditioning loop supplied water at approximately 14.4°C (58°F) in accordance with DOE's test procedure (10 CFR 430, Subpart B). Table 3 presents the nominal test conditions and permissible test condition ranges specified within the DOE test procedure.

Table 3. Water Heater Test Conditions

Test Condition	Nominal Value	Permissible Variation
Daily Hot Water Removal	243.4 L (64.3 gallon)	±3.8 L (± 1 gallon)
Draw Flow Rate	11.4 L/min (3.0 gallon/min)	±1.0 L/min (±0.25 gallon/min)
Storage Tank Temperature	57.2°C (135.0°F)	±2.8°C (± 5.0°F)
Supply Water Temperature	14.4°C (58°F)	±1.1°C (± 2.0°F)
Ambient Temperature	19.7°C (67.5°F)	±0.6°C (± 2.5°F)

An infrared thermography system was used to determine if there were any voids in the water heaters' insulation system. An image of the water heater's surface temperature identified any voids in the insulation between the storage tank and the outer metal jacket. It also identified areas of heat loss resulting from piping penetrations through the water heater's outer jacket or other high thermal conductance paths.

RESULTS

Measurements of Thermal Conductivity (λ)

Table 4 summarizes the test conditions and measured thermal conductivity for the polyurethane foam block specimens produced using the three blowing agents, HCFC-141b, H_2O/CO_2, and HFC-245fa. As previously noted, the 1-meter guarded hot plate apparatus was used in the double-sided mode of operation. Thus, the thermal conductivity measurements represent the average of two specimens produced with each of the blowing agents.

Column 2, in Table 4, is the average thickness of the top and bottom specimens. The temperature and pressure of the ambient air surrounding the specimens during each test are tabulated in columns 3 and 4, respectively. The mean temperature of the specimen and the temperature difference between the hot and cold sides of the specimen are listed in columns 5 and 6, respectively. The measured thermal conductivity (λ) for each set of specimens are listed in column 7.

Table 4. Thermal Conductivity Measurements of Polyurethane Foams

Test	L_{avg}		T_a		P_a		T_m		ΔT		λ	
	mm	in.	°C	°F	kPa	in.Hg	°C	°F	°C	°F	$\frac{W}{m \cdot K}$	$\frac{Btu \cdot in.}{h \cdot ft^2 \cdot °F}$
A1	65.36	2.575	28.8	83.8	99.50	29.47	28.8	83.3	18.1	32.60	0.0214	0.148
A2	65.35	2.575	34.3	93.8	98.61	29.20	34.3	93.8	29.2	52.60	0.0221	0.153
A3	65.34	2.572	39.9	103.8	98.28	29.10	39.9	103.8	40.3	72.50	0.0229	0.159
B1	65.14	2.565	28.7	83.7	98.82	29.26	28.8	83.8	18.1	32.60	0.0305	0.211
B2	65.12	2.564	34.3	93.8	97.79	28.96	34.3	93.8	29.2	52.60	0.0314	0.218
B3	65.07	2.562	39.9	103.8	98.34	29.12	39.9	103.8	40.3	72.50	0.0324	0.225
C1	65.65	2.585	28.7	83.7	99.63	29.50	28.8	83.8	18.1	32.60	0.0207	0.144
C2	65.64	2.584	34.3	93.8	99.79	29.55	34.3	93.8	29.2	52.60	0.0214	0.149
C3	65.62	2.583	39.9	103.8	99.68	29.52	39.9	103.8	40.3	72.50	0.0221	0.153

Tests A1-A3 - Blowing Agent HCFC-141b - Elapsed time After Production 27-29 Days
Tests B1-B3 - Blowing Agent H_2O/CO_2 - Elapsed Time After Production 27-29 Days
Tests C1-C3 - Blowing Agent HFC-245fa - Elapsed Time After Production 26-29 Days
Relative humidity of the ambient air for all the tests was less than 10%.

Thermal conductivity values are plotted in Figure 4 as a function of mean temperature. The conductivity of polyurethane foams produced using the H_2O/CO_2 as the blowing agent was approximately 42% greater than the conductivity of foams using HCFC-141b. The conductivity of polyurethane foams produced using HFC-245fa was approximately 3% lower than the conductivity of polyurethane foams using HCFC-141b blowing agent.

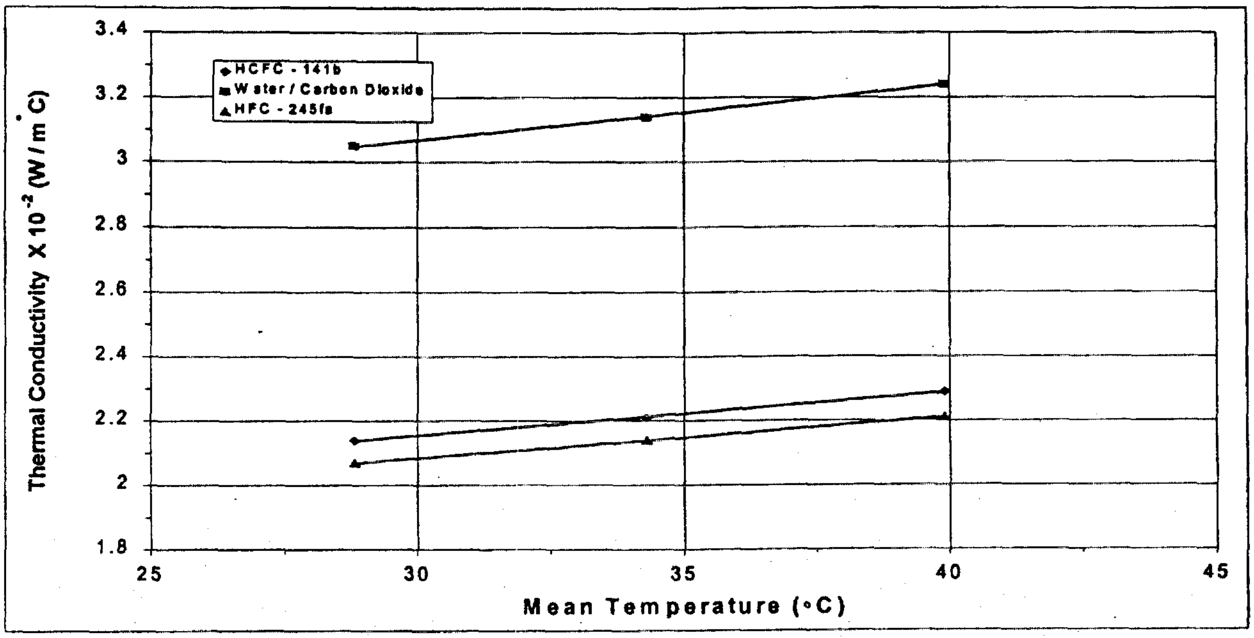

Figure 3. Thermal Conductivity of Polyurethane Foams Versus Mean Specimen Temperature

Energy Factor Measurements

The test conditions and measured energy factors for the four water heaters manufactured with foam insulation using HCFC-141b, H_2O/CO_2, and HFC-245fa blowing agents are summarized in Fanney et al. (1999). A series of four to six 24-hour simulated use tests were conducted for each water heater. The results for the first day of each test series were not included in the computation of the average energy factors or the standard deviations. During the first day, the materials used in the water heater's construction may not be in thermal equilibrium with the stored water. This issue is addressed by allowing the water heater's thermostats to cycle up to three times before a test commences (10 CFR 430, Subpart B).

The average energy factors for the four water heaters using HCFC-141b as the blowing agent ranged from 0.885 to 0.892 with an average value of 0.887. The largest standard deviation between test results for a single tank was 0.0016 whereas the standard deviation between tanks was 0.0028.

The average energy factor for each of the water heaters within the H_2O/CO_2 group ranged from 0.867 to 0.872. The average energy factor for the four water heaters using H_2O/CO_2 as the blowing agent is 0.870 with an associated standard deviation of 0.0021.

The average energy factor for the four water heaters manufactured using the HFC-245fa blowing agent ranged from 0.881 to 0.886 with an average energy factor of 0.884. The largest variability in energy factor results was from 0.882 to 0.889, resulting in a standard deviation of 0.0023. The standard deviation associated with the average energy factor for the four tanks within this group was 0.0018.

Figure 4 shows the average energy factor for each set of four tanks and the uncertainty associated with each value. These results show that the average energy factor for water heaters manufactured using HCFC-141b as the blowing agent was slightly higher than that measured for the water heaters that utilized HFC-245fa as the blowing agent (0.887 compared to 0.884). The 0.870 average energy factor for the four tanks manufactured using H_2O/CO_2 is 0.017 (1.9%) and 0.014 (1.6%) lower than the average energy factors measured for the water heaters manufactured using the HCFC-141b and HFC-245fa blowing agents, respectively.

Overall Heat-Loss Coefficient (UA) Measurements

The average overall heat-loss coefficient (UA) for the water heaters manufactured using the HCFC-141b blowing agent is 1.46 W/°C (3.11 Btu/hr °F). The average coefficient measured for the water heaters manufactured with HFC-245fa was 1.48 W/°C (3.14 Btu/hr °F), or 1.3% greater. The average coefficient for water heaters manufactured with the H_2O/CO_2 blowing agent is 1.77 W/°C (3.76 Btu/hr °F) or 21% and 20% greater than the average heat-loss coefficient for water heaters produced using HCFC-141b and HFC-245fa blowing agents.

It is interesting to note that, although the average overall heat-loss coefficient for water heaters with the H_2O/CO_2 blowing agent was 21% higher than that for the water heaters with HCFC-141b blowing agent, 1.77 W/°C versus 1.46 W/°C, the average energy factor was only 1.9% lower (0.870 versus 0.887). This is because in addition to the heat conducted through the insulation, the heat loss from the water stored within the water heater is the result of thermal losses associated with piping penetrations and thermal short circuits that may exist between the storage tank and the surrounding jacket.

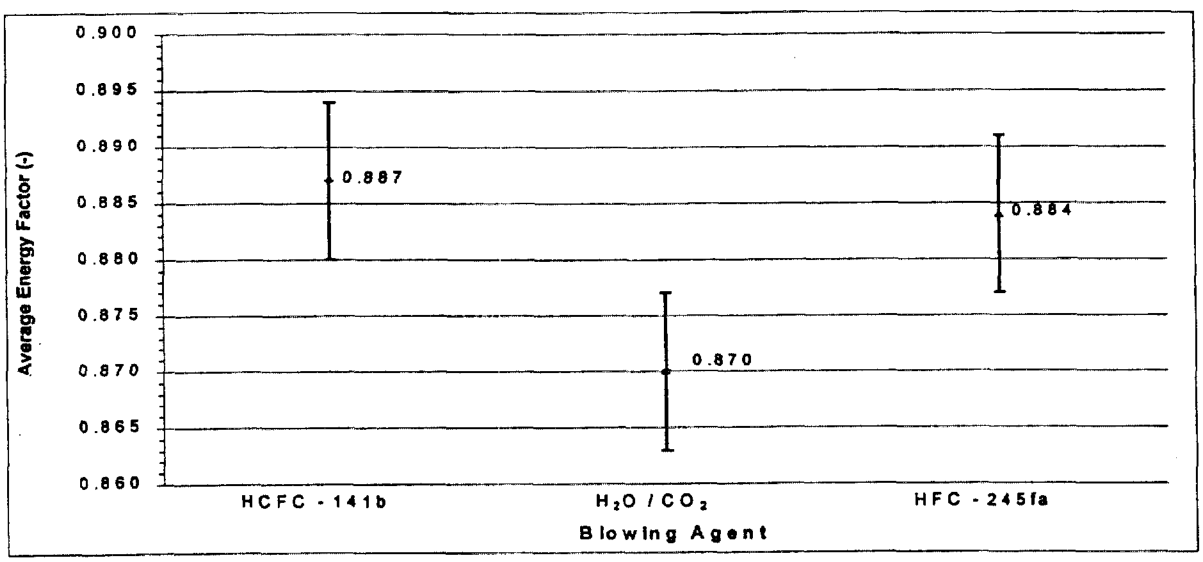

Figure 4. Average Energy Factor for Water Heaters Produced Using Each Blowing Agent

The average heat loss attributable to thermal short circuits, expressed as a percentage of the total, for water heaters manufactured using HCFC-141b and HFC-245fa, are essentially the same, 36% and 38% respectively. The thermal short circuits accounted for only 30% of the heat loss from the water heaters manufactured with H_2O/CO_2 as the blowing agent. As the thermal conductivity of the foam insulating material increases, the overall heat-loss coefficient associated with the insulation increases, resulting in a lower percentage of the total heat loss being attributable to thermal short circuits.

Examples of thermal short circuits are readily identified using infrared thermography, Figure 5. This image shows significant temperature elevations associated with the piping penetrations, the heating element access covers, and the water heater's lower perimeter.

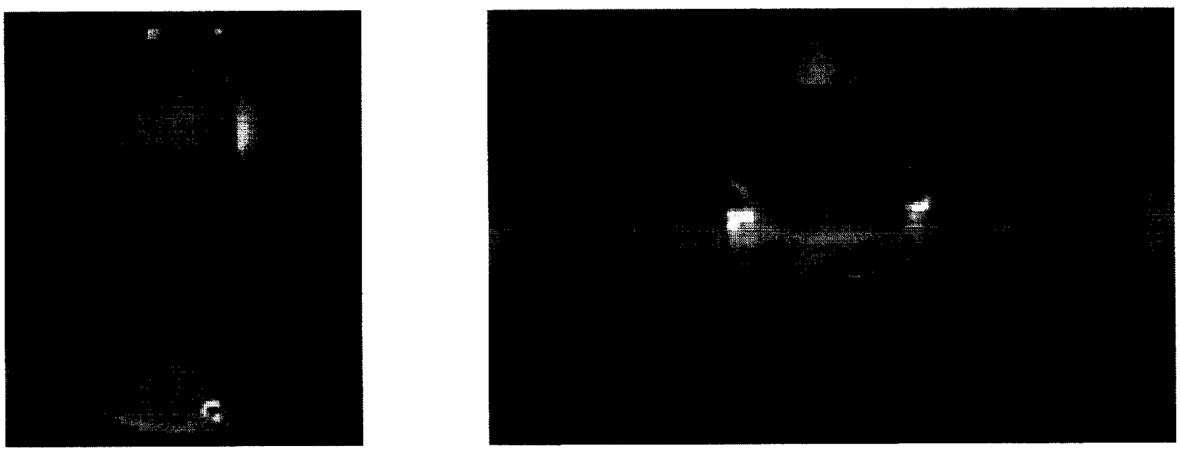

Figure 5. Infrared Image of Front (Left) and Top (Right) of an Electric Water Heater

CONCLUSIONS

Polyurethane foams were manufactured using three blowing agents, HCFC-141b, H_2O/CO_2, and HFC-245fa. The foams were produced in block form for thermal conductivity measurements and as insulation used in the construction of residential electric water heaters. The thermal conductivity of the foam specimens was measured using a 1-meter guarded hot plate apparatus at three mean temperatures by maintaining the cold plate at 19.7°C (67.5°F) and operating the hot plate at nominal temperatures of 51.7°C (125°F), 57.2°C (135°F), and 62.8°C (145°F). The thermal conductivity of the polyurethane foam specimens produced using HCFC-141b, the blowing agent currently used by water heater manufacturers, at a mean temperature of 34.3°C (66.3°F), is 0.0221 W/m K. At identical measurement conditions, the thermal conductivity of the specimens produced using HFC-245fa and H_2O/CO_2 were measured to be 0.0214 W/m K (0.148 Btu in./hr ft^2 F) and 0.0314 W/m K (0.218 Btu in./hr ft^2 F), respectively. The thermal conductivity of the foam specimens increased linearly with the specimen's mean temperature.

Three sets of four water heaters were insulated with each of the three polyurethane insulation materials. The energy factor and overall heat-loss coefficient (UA) were measured for each of the twelve water heaters. The 24-hour simulated use test, used to determine the energy factor, was repeated up to seven times for an individual water heater to ensure the test procedure's repeatability. The average energy factor for the four water heaters manufactured with the blowing agent HCFC-141b, was 0.887. Use of the HFC-245fa blowing agent resulted in an average energy factor of 0.884. Water heaters insulated with H_2O/CO_2 based polyurethane foam resulted in an average energy factor of 0.870.

The uncertainty associated with the energy factor measurements is ± 0.007.

The UA quantifies the thermal integrity of a water heater. It includes heat loss through the insulation surrounding the storage tank as well as heat conducted through piping penetrations and other thermal short circuits. Tests were conducted on each of the water heaters to measure its overall heat-loss coefficient. The average UA for the four water heaters manufactured using the HCFC-141b, HFC-245fa, and H_2O/CO_2 blown polyurethane foams are, respectively, 1.46 W/°C (3.11 Btu/hr °F), 1.48 W/°C (3.14 Btu/hr °F), and 1.77 W/°C (3.76 Btu/hr °F). The measurement uncertainty associated with the UA measurements is ± 0.02 W/°C (± 0.04 Btu/hr °F). Calculations determined the fraction of the total heat loss attributable to piping penetrations and thermal short circuits as approximately 38%.

ACKNOWLEDGEMENTS

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